PKG 815

Lab 1

Water Vapor Permeability (WVP) of Packaging Materials and Fabricated Package Systems

Submitted to

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Abstract

The objective of the provided study is to study the water vapor permeability of low-density polyethylene (LDPE) films and fabricated package systems like pouches. The water vapor permeability of the packaging materials is a crucial property as it determines the shelf life, quality and stability of the packaged product. Gravimetric method and PERMATRAN W3/34 were used to calculate the water vapor permeability and study discussed the effects of various relative humidity and temperature values.

It was found that increasing the temperature from 20°C to 40°C increase the permeability of LDPE films. When it comes to the changing relative humidity from 100% to 50%, it slightly decreases the permeability values of the tested films and the activation energy values.

Introduction and Objectives

The rapid expansion of the global population necessitates addressing the critical issues of food quality, quantity, and safety. Any alteration in the quality of food products can lead to spoilage, rendering them unsuitable for human consumption. Food spoilage is widely recognized as a primary challenge within the food industry[1]. Food loss and waste create major economic and environmental problems. Wasted food costs billions of dollars every year. When food ends up in landfills, it releases methane gas. Methane is about 25 times more potent than carbon dioxide in causing climate change[2]. The deterioration of food quality is often attributed to moisture transfer, loss, or gain resulting from interactions with the atmosphere. These processes induce swelling, shrinkage, breakdown, softening, or toughening, primarily driven by phase transitions and dissolution mechanisms[3].

Packaging materials and systems play an important role in mitigating the rate of food deterioration, thereby enhancing food preservation. Beyond serving as mere containers, packaging provides protection for food products against external factors, contributing to maintaining their quality and extending shelf life. Plastic films are widely used as barriers between food and the external environment due to their superior mechanical, chemical, and physical properties, as well as their cost-effectiveness compared to alternative materials. However, moisture permeation through plastic films during storage remains a concern. Therefore, it is essential to establish reliable methods for measuring the permeability of packaging materials. Such measurements enable the prediction of product shelf life[4].

Moisture gain over time can lead to rancidity and browning of food products. Selection of packaging materials directly influences the rate at which these changes occur. Consequently, the choice of polymer for food packaging plays a critical role in determining the product's shelf life. Low-density polyethylene (LDPE) is widely utilized in food packaging due to its advantageous properties, including ease of processing, good impact resistance, and chemical inertness[5].

This study focuses on the water vapor transmission rate (WVTR) of LDPE films and pouches. One objective of this research is to familiarize with the experimental procedures for measuring the WVTR of both packaging films and fabricated packages. Additionally, the study aims to evaluate the influence of environmental factors, such as temperature and relative humidity, on WVTR and to determine the water vapor transmission rates of the selected films.

Previous studies have documented the effects of temperature and humidity on the WVTR of various packaging materials. For instance, Yin et al. examined the influence of relative humidity and temperature on the WVTR of biaxially-oriented polyvinyl alcohol (BOPVA) and polypropylene (BOPP) films. Their findings indicated that an increase in humidity led to higher WVTR values for the selected films. This phenomenon was attributed to the formation of hydrogen bonds between the hydroxyl groups in the polymer chain segments and water molecules. Similar results have also been observed for polyethylene films. Regarding the effect of temperature, the researchers maintained a constant relative humidity of 50% and incrementally increased the temperature from 20°C to 40°C. Their investigation revealed that higher temperatures lead to increased water vapor transmission under fixed relative humidity conditions[6]. Similar results have also been observed for polyethylene films[7].

In the first part of the report, the permeance and permeability of samples will be determined and will be used for finding activation energy for each relative humidity values (50% and 100%) with the aid of relationship by creating the graph between lnP and inverse temperature values. Second part involves the calculation of the predicted permeability of the LDPE pouches at 50% and 100% relative humidity. The WVTR values will be obtained from dividing the slope of the plot between net weight gain and time by area.

Materials and Methods

Several test methods are available for measuring water vapor permeability, with the gravimetric method being the most widely used. This technique determines the WVTR by measuring weight changes resulting from water vapor passing through the test material over a specified time under

controlled conditions. This method is based on ASTM E96 standards. The gravimetric method is categorized into two types: the desiccant method and the water method. In the desiccant method, the material is sealed over the open mouth of a test dish containing a desiccant. The rate of water vapor transfer from the material to the desiccant is determined through weighing over the given period of time. In the water method, the test dish is filled with distilled water. Periodic weighing is conducted to determine the rate of water vapor movement from the water through the specimen to the atmosphere[8].

In the present study, LDPE pouches with an area of 100 cm^2 were prepared using the desiccant method. Each pouch was filled with approximately 20–25 g of desiccant and sealed. A total of four pouches were prepared: three containing desiccants and one serving as a control. The sealed pouches were then placed inside a controlled chamber maintained at a temperature of 37.8°C and a relative humidity of 85%. The weight gain of the pouches was measured at two-day intervals over a 14-day period, and a graph was plotted to represent weight gain versus time. Before each weighing, the pouches were allowed to equilibrate to ambient temperature. This process was repeated until a constant rate of water vapor transmission was observed[9].

The gravimetric method is generally regarded as a time-consuming technique due to the extended duration of the experimental procedure. To address this limitation, advanced equipment for measuring the water vapor transmission rate (WVTR) of films and packages has been developed by Modern Controls Inc. (Mocon)[9]. The apparatus is called as PERMATRAN W3/34. The PERMATRAN W3/34 is equipped with a dual-head instrument, enabling the determination of WVTR across a wide range of barrier materials and package types. It accommodates variations in material properties such as thickness, surface texture, transmission rate, and equilibrium time It is comprised of different parts, such as diffusion cell which properly determines a circular area, diffusion cell temperature control to thermostatically control the diffusion cell temperature to within around 0.6°C, flowmeter, flow-switching valves, infrared sensor, recording device, desiccant drying system, flow-metering valve[10]. There are also several reagents and materials such as, distilled water for getting relative humidity, reference film for calibration, sealing grease and nitrogen gas in the equipment system.

The WVTR of LDPE films with a thickness of 1.25 mm is determined using the PERMATRAN W3/34 apparatus in this study. The experiments are conducted at three different temperatures: 20°C, 30°C, and 40°C. For each temperature, the relative humidity is varied between two levels, 50% and 100%. The collected data is analyzed using the Van't Hoff-Arrhenius relationship.

The data interpretation will be conducted using Microsoft Excel.

Results and Data Analysis

Part A) Water Vapor Transmission Rates of LDPE Films Using PERMATRAN W3/34

For 100% relative humidity:

To calculate the saturated pressure of the permeant at the testing temperatures which are 20, 30 and 40°C, which is essential for determining the permeance, the Antoine equation is employed. The Antoine equation, expressed as shown in Equation 1:

$$p^{sat}=10^{A-\frac{B}{T+C}} \quad (1)$$

A, B and C are Antoine constants for water in the temperature range from 1 to 99°C. The constants are given in the Table 1. Temperature unit in the equation is Kelvin, while pressure unit is mmHg:

Table 1: Antoine constants for water

Antoine constants for water in the temperature range from 1 to 99 °C	
A	8.07131
B	1730.63
C	233.426

Let's calculate saturated pressure values for all three testing temperatures:

$$p^{sat}=10^{8.07131-\frac{1730.63}{20+233.426}}=17.473\,mmHg$$

$$p^{sat}=10^{8.07131-\frac{1730.63}{30+233.426}}=31.74\,mmHg$$

$$p^{sat}=10^{8.07131-\frac{1730.63}{40+233.426}}=55.193\,mmHg$$

For calculating the saturated pressure, relative humidity does not play a role. However, it becomes a critical factor in determining the pressure change, which is calculated using Equation 2:

$$\Delta p = p^{sat} \frac{RH_0}{100}$$

In the first scenario, relative humidity is 100%, so pressure change values are as same as saturated pressures for all three testing temperatures:

$$\Delta p = p^{sat} \frac{100}{100} = p^{sat} \qquad 2$$

So,

$$\Delta p at 20\,°C = 17.473\, mmHg$$

$$\Delta p at 30\,°C = 31.74\, mmHg$$

$$\Delta p at 40\,°C = 55.193\, mmHg$$

After obtaining the pressure change values, permeance (Z) values can be calculated from Equation 3:

$$Z = \frac{WVTR}{\Delta p} \qquad 3$$

The unit of permeance is $\frac{g(H_2O)}{m^2 \bullet day \bullet mmHg}$. Using average WVTR data of

Table 2: WVTR values

Data points	Thickness of films: 1.25 mil			Thickness of films: 1.25 mil			Thickness of films: 1.25 mil		
	20.0 ± 1.0 °C			30 ± 1.0 °C			40 ± 1.0 °C		
	Replicate 1	Replicate 2	Replicate 3	Replicate 1	Replicate 2	Replicate 3	Replicate 1	Replicate 2	Replicate 3
1	2.6606	2.6096	2.8282	6.5528	6.3544	6.3346	15.4488	15.9454	15.3568
2	2.6784	2.6132	2.8206	6.5296	6.3830	6.3436	15.5246	16.0236	15.3856
3	2.667	2.5596	2.8274	6.5184	6.3726	6.3436	15.5214	16.0486	15.4340
4	2.6562	2.5884	2.8086	6.5014	6.3860	6.3508	15.5714	16.1338	15.4584
5	2.6468	2.6182	2.8092	6.5102	6.407600	6.3520	15.5924	16.1342	15.4768
Average	2.661800	2.597800	2.818800	6.522480	6.380720	6.344920	15.531720	16.057120	15.422320
Permeance in g/day*m^2*mmHg	0.152337893	0.148675099	0.161323184	0.205497164	0.201030876	0.199902962	0.281407425	0.290926748	0.279425289
Permability in g*mil/day*m^2*mmHg	0.190422366	0.185843873	0.20165398	0.256871456	0.251288595	0.249878702	0.351759281	0.363658435	0.349281612
LnP	-1.658510695	-1.682848348	-1.601202019	-1.359179492	-1.38115322	-1.386779671	-1.044808198	-1.011540217	-1.051876772
1/T	0.003411223	0.003411223	0.003411223	0.003298697	0.003298697	0.003298697	0.003193358	0.003193358	0.003193358

three replicates:

$$Z at 20\,°C for Replicate 1 = \frac{2.662 \frac{g(H_2O)}{m^2 \bullet day}}{17.473\, mmHg} = 0.152 \frac{g(H_2O)}{m^2 \bullet day \bullet mmHg}$$

$$Z at 30\,°C for Replicate 2 = \frac{6.381 \frac{g(H_2O)}{m^2 \bullet day}}{31.74\, mmHg} = 0.201 \frac{g(H_2O)}{m^2 \bullet day \bullet mmHg}$$

$$Z\,at\,40\,°C\,for\,Replicate\,3=\frac{15.422\,\frac{g(H_2O)}{m^2\bullet day}}{55.193\,mmHg}=0.279\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}$$

Permeability is calculated by multiplying the permeance by the thickness of the material. The permeability unit is $\frac{g(H_2O)}{m\bullet day\bullet mmHg}$:

$P=\frac{WVTR\times l}{\Delta p}=Z\times l$ To calculate the permeability for each temperature values:

$$P\,at\,20\,°C\,for\,Replicate\,1=0.152\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.19\,\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

$$P\,at\,30\,°C\,for\,Replicate\,2=0.201\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.251\,\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

$$P\,at\,40\,°C\,for\,Replicate\,3=0.279\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.349\,\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

Next step is the determination of activation energy by using Van't Hoff-Arrhenius relationship (Equation 5). The graph between ln P and 1/T is plotted:

$$P=P_0\,e^{\frac{-E_a}{RT}}$$

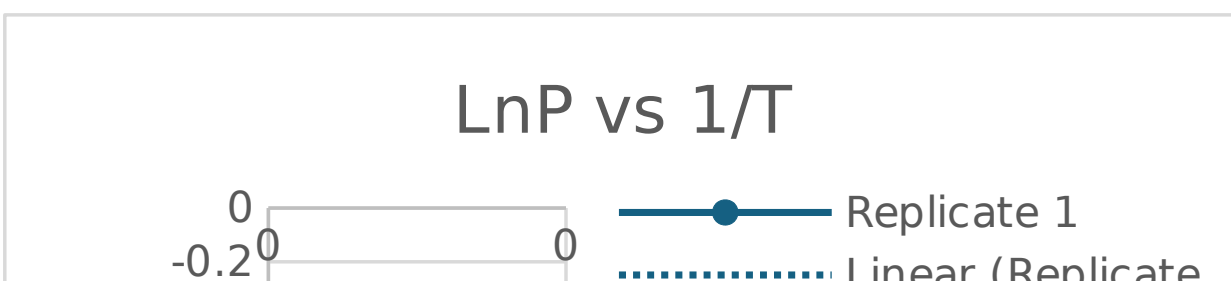
$$LnP=\ln P_0-\frac{E_a}{RT}$$

Table 2: Ln P and 1/T value of

Table 4: Ln P and 1/T value of Replicate 2

Replicate 2	
LnP	1/T
-1.682848348	0.003411223
-1.38115322	0.003298697
-1.011540217	0.003193358

Table 5: Ln P and 1/T value of



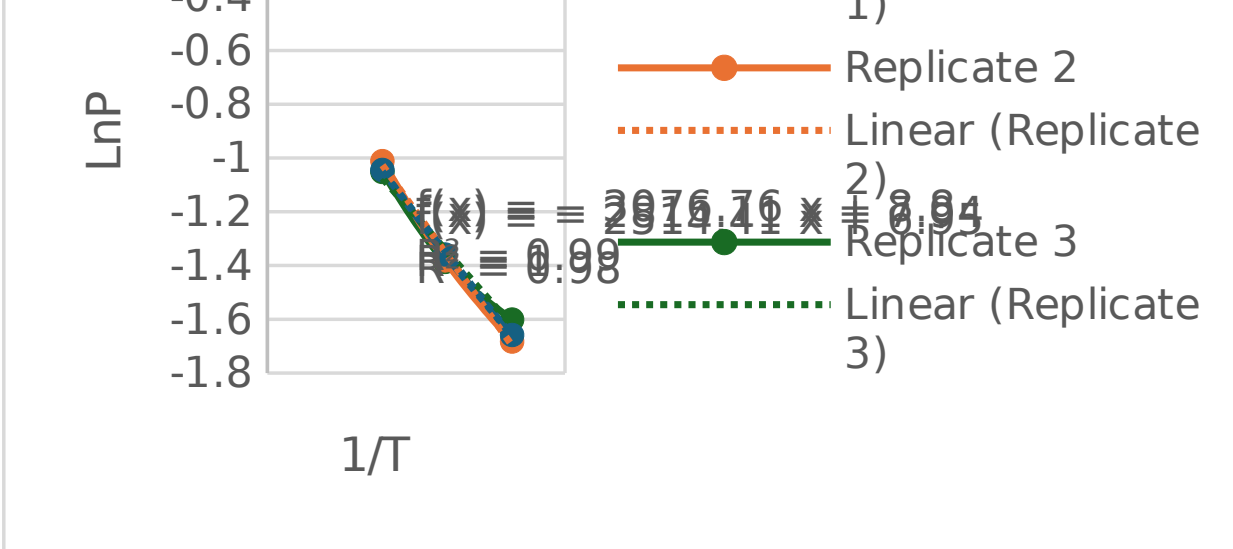


Figure 1:Ln P vs 1/T for each replicate when RH is 100%

Activation energy of the first replicate is calculated by using the slope (m) of the linear trendline of the above-given graph:

$$y=-2815.1\,x+7.9388 LnP=\ln P_0-\frac{E_a}{RT}$$

So, $y=LnP$, $x=\frac{1}{T}$, $\ln P_0=7.9388$, $\frac{-E_a}{R}=-2815.1$ and $R=8.314\frac{J}{mol\bullet °K}$:

$$\frac{-E_a}{R}=-2815.1$$

$$E_a=2815.1\bullet 8.314\frac{J}{mol\bullet °K}=23404.741\frac{J}{mol}$$

Same steps are followed for finding the activation energies of the other two replicates. The below given table summarizes all the results:

Table 6: Result summary for 100% RH

	Replicate 1	Replicate 2	Replicate 3
Universal Gas constant (R)	8.314	8.314	8.314
E_a/R	2815.1	3076.8	2514.4
E_a	23404.7414	25580.5152	20904.7216
Average	23296.6594		

For 50% relative humidity:

The saturated pressure values corresponding to the selected temperatures remain constant regardless of changes in relative humidity. Therefore, the same values will be utilized for calculating pressure changes at 50% relative humidity:

$$\Delta p = p^{sat} \frac{50}{100} = \frac{p^{sat}}{2}$$

$$\Delta p at 20\ °C = 8.737\ mmHg$$

$$\Delta p at 30\ °C = 15.87\ mmHg$$

$$\Delta p at 40\ °C = 27.597\ mmHg$$

Equation 3 is subsequently employed to calculate the permeance values under conditions of 50% relative humidity by using average WVTR data of three replicates:

Table 7: WVTR values

Data points	Thickness of films: 1.25 mil			Thickness of films: 1.25 mil			Thickness of films: 1.25 mil		
	20.0 ± 1.0 ˚C			30 ± 1.0 ˚C			40 ± 1.0 ˚C		
	Replicate 1	**Replicate 2**	**Replicate 3**	**Replicate 1**	**Replicate 2**	**Replicate 3**	**Replicate 1**	**Replicate 2**	**Replicate 2**
1	1.1068	1.0978	1.1442	2.7146	2.6912	2.9184	5.9626	5.866	6.3158
2	1.0962	1.1058	1.1548	2.7140	2.6882	2.8986	5.8314	5.7214	6.4196
3	1.1150	1.1156	1.1738	2.7198	2.6888	2.8880	5.7798	5.6702	6.3942
4	1.0876	1.0782	1.1434	2.7060	2.6694	2.8804	5.7800	5.5908	6.3442
5	1.0780	1.0876	1.1236	2.7010	2.6682	2.8728	5.7526	5.6124	6.3742
Average	1.096720	1.097000	1.147960	2.711080	2.681160	2.891640	5.821280	5.692160	6.369600
Permeance in g/day*m^2*mm	0.125525924	0.125557972	0.131390638	0.170830498	0.16894518	0.18220794	0.210942692	0.206263838	0.230811878
Permability in g*mil/day*m^2* mmHg	0.156907	0.156947	0.164238	0.213538	0.211181	0.227760	0.263678	0.257830	0.288515
lnP	-1.852099	-1.851844	-1.806437	-1.543940	-1.555037	-1.479463	-1.333025	-1.355456	-1.243009
1/T	0.003411223	0.003411223	0.003411223	0.003298697	0.003298697	0.003298697	0.003193358	0.003193358	0.003193358

$$Z at 20\ °C for Replicate 1 = \frac{1.097 \frac{g(H_2O)}{m^2 \bullet day}}{8.737\ mmHg} = 0.126 \frac{g(H_2O)}{m^2 \bullet day \bullet mmHg}$$

$$Z\,at\,30\,°C\,for\,Replicate\,2=\frac{2.681\,\frac{g(H_2O)}{m^2\bullet day}}{15.87\,mmHg}=0.169\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}$$

$$Z\,at\,40\,°C\,for\,Replicate\,3=\frac{6.369\,\frac{g(H_2O)}{m^2\bullet day}}{27.597\,mmHg}=0.231\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}$$

Equation 4 is applied to calculate the permeability values for 50% relative humidity:

$$P\,at\,20\,°C\,for\,Replicate\,1=0.126\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.157\,\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

$$P\,at\,30\,°C\,for\,Replicate\,2=0.169\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.211\,\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

$$P\,at\,40\,°C\,for\,Replicate\,3=0.231\,\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.289\,\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

Once again, a graph should be plotted with ln P on the y-axis and 1/T on the x-axis to determine the activation energy:

Table 8: Ln P and 1/T values for Replicate 1

Replicate 1	
LnP	1/T
-1.852099	0.003411223
-1.543940	0.003298697
-1.333025	0.003193358

Table 9: Ln P and 1/T values for

Table 10: Ln P and 1/T values for Replicate 3

Replicate 3	
LnP	1/T
[illegible]	[illegible]

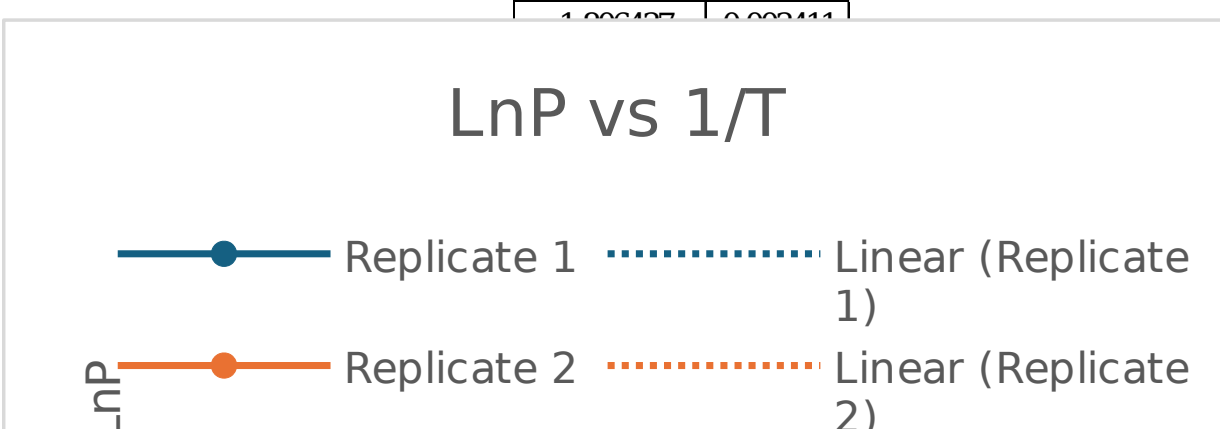


Figure 2: Ln P vs 1/T for each replicate when RH is 100%

So, $y=LnP$, $x=\frac{1}{T}$, $\ln P_0=6.302$, $\frac{-E_a}{R}=-2386.6$ and $R=8.314\frac{J}{mol\bullet °K}$:

$$\frac{-E_a}{R}=-2386.6$$

$$E_a=2386.6\bullet 8.314\frac{J}{mol\bullet °K}=19842.192\frac{J}{mol}$$

Same steps are followed for finding the activation energies of the other two replicates. The below given table summarizes all the results:

Table 11: Result summary for 50% RH

	Replicate 1	Replicate 2	Replicate 3
Universal Gas constant (R)	8.314	8.314	8.314
E_a/R	2386.6	2282.5	2589.8
E_a	19842.1924	18976.705	21531.5972
Average	20116.83153		

Statistical tests such as F-test and t-test are performed and results are given below:

Table 12: F-Test Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	23296.6594	20116.83153
Variance	3649681.824	1125625.686
Observations	4	4
df	3	3
F	3.242358335	
P(F<=f) one-tail	0.179906701	
F Critical one-tail	9.276628153	

Table 13: t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	23296.6594	20116.83153
Variance	3649681.824	1125625.686
Observations	4	4
hesized Mean Dif	0	
df	5	
t Stat	2.910267671	
P(T<=t) one-tail	0.016694655	
t Critical one-tail	2.015048373	
P(T<=t) two-tail	0.033389311	

Part B) Determination of the Water Vapor Transmission Rate of LDPE Pouches

The below given formula is used to calculate the net wight gain (Q_t¿ of pouches filled with desiccant:

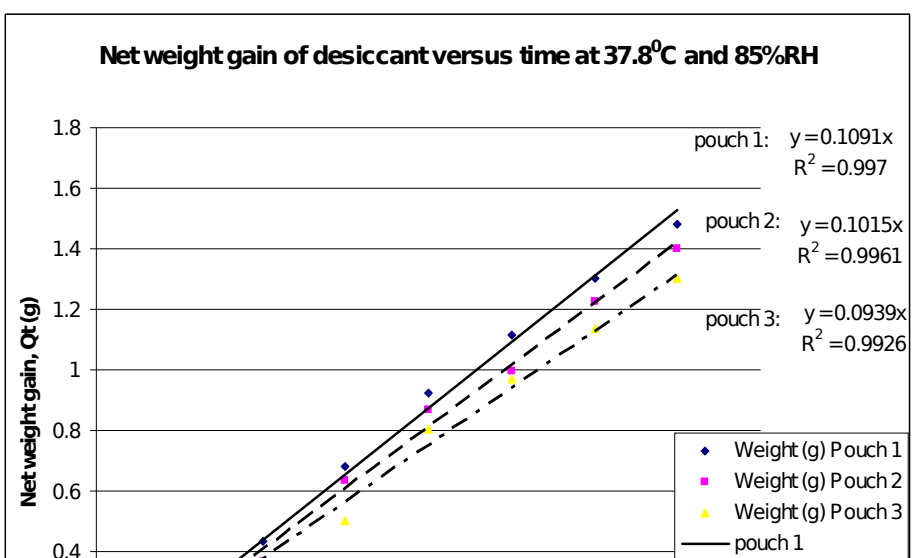
$$Q_t = (T_t - T_i) - (C_t - C_i) \qquad 5$$

By plotting Q versus time, we can calculate the slope of the line which gives us the value of Q/t. Using this value, we can calculate the transmission rate, permeance, and permeability of the LDPE film at 37.8°C and 85% relative humidity.

The slope of the line from the graph plotted between Q_t and t gives the $\frac{Q_t}{t}$ which is used for the calculation of the WVTR:

Table 14: Net weight gain values

Time in days	2	4	6	8	10	12	14
Net weight gain in g for Pouch 1	0.22	0.42	0.67	0.92	1.16	1.33	1.44
Net weight gain in g for Pouch 2	0.21	0.38	0.62	0.88	1.05	1.22	1.39
Net weight gain in g for Pouch 3	0.19	0.32	0.53	0.8	0.97	1.17	1.31



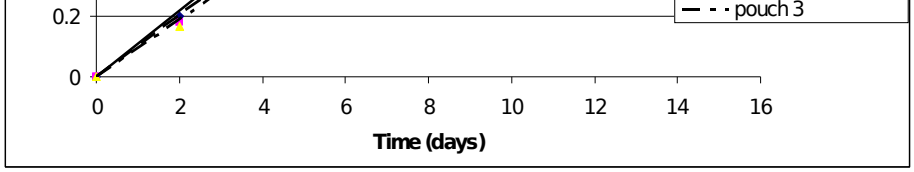


Figure 3: Net weight gain vs time

Where area is

$A = 10\,cm \bullet 10\,cm \bullet 2 = 200\,cm^2 = 0.02\,m^2$

The slopes of lines for all three pouches are:

Table 15: Slope

Pouch	Slope
1	0.1091
2	0.1015
3	0.0939

Using area and slope values:

$$WVTR_{Pouch1} = \frac{0.1091}{0.02} = 5.455\,\frac{g(H_2O)}{m^2 \bullet day}$$

$$WVTR_{Pouch2} = \frac{0.1015}{0.02} = 5.075\,\frac{g(H_2O)}{m^2 \bullet day}$$

$$WVTR_{Pouch3} = \frac{0.0939}{0.02} = 4.695\,\frac{g(H_2O)}{m^2 \bullet day}$$

To calculate the permeance, the saturated pressure at the given temperature (37.8 $°C$) must first be determined. This is achieved using the Antoine equation:

$$p^{sat} = 10^{8.07131 - \frac{1730.63}{37.8 + 233.426}} = 49.039\,mmHg$$

Change in pressure for 85% relative humidity:

$$\Delta p = p^{sat}\frac{85}{100} = p^{sat} = 41.683\,mmHg$$

Permeance values are obtained:

$$Z_{Pouch1} = \frac{5.455\,\frac{g(H_2O)}{m^2 \bullet day}}{41.683\,mmHg} = 0.131\,\frac{g(H_2O)}{m^2 \bullet day \bullet mmHg}$$

$$Z_{Pouch2} = \frac{5.075\,\frac{g(H_2O)}{m^2 \bullet day}}{41.683\,mmHg} = 0.122\,\frac{g(H_2O)}{m^2 \bullet day \bullet mmHg}$$

$$Z_{Pouch3}=\frac{4.695\frac{g(H_2O)}{m^2\bullet day}}{41.683\,mmHg}=0.113\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}$$

Permeability values are:

$$P_{Pouch1}=0.131\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.164\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

$$P_{Pouch2}=0.122\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.153\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

$$P_{Pouch3}=0.113\frac{g(H_2O)}{m^2\bullet day\bullet mmHg}\bullet 1.25\,mil=0.141\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

All the obtained values are systematically presented in the accompanying table:

Table 16: Values for WVTR, Permeance, and Permeability of each pouch

Pouch	Slope	WVTR	Permeance, Z	Permeability, P
1	0.1091	5.455	0.131	0.164
2	0.1015	5.075	0.122	0.153
3	0.0939	4.695	0.113	0.141

From the above given table, the average permeability values of three pouches can be calculated:

$$P_{ave}=\frac{0.164+0.153+0.141}{3}=0.153\frac{g(H_2O)\bullet mil}{m^2\bullet day\bullet mmHg}$$

To predict the permeability, the activation energy values form the part A and Van't Hoff-Arrhenius relationship are used. For 100% relative humidity, the activation energy was calculated as $23316.613\frac{J}{mol}$, while $19999.327\frac{J}{mol}$ was determined for 50% relative humidity. Recalling Van't Hoff-Arrhenius relationship, the predicted permeability for these two relative humidity values:

$P = P_0 e^{\frac{-E_a}{RT}}$ Here, P_0 is the average permeability value of three pouches in 85% relative humidity and 38.7 $°C$.

Predicted permeability in 100% relative humidity:

$$P_{100\%} = 0.153 \bullet e^{\frac{-23296.659}{8.314 \cdot 310.95}} = 1.85 \cdot 10^{-5} \frac{g(H_2O) \bullet mil}{m^2 \bullet day \bullet mmHg}$$

$Predicted\, permeability \in 50\%\, relative\, humidity$:

$$P_{50\%} = 0.153 \cdot 10^{-6} e^{\frac{-20116.832}{8.314 \cdot 310.95}} = 6.66 \cdot 10^{-5} \frac{g(H_2O) \bullet mil}{m^2 \bullet day \bullet mmHg}$$

Discussions

Applications of WVTR in food packaging. Water vapor permeability (WVP) is among the most extensively studied characteristics of packaging films due to the critical role of water in spoilage reactions, food freshness, crispiness, and dehydration prevention. WVP is defined as the amount of water that permeates through the packaging film per unit area, time, and pressure difference. The water vapor transmission rate (WVTR), measured using various methods outlined in the introduction of this study, serves as the basis for WVP calculations. As WVTR directly influences the preservation of appearance, color, texture, taste, and overall acceptability. Almost all foods lose their odor, texture, aroma, flavor in the case of being exposed to too much moisture due to low level sensitivity to moisture. To prevent moisture-induced deterioration, preserve texture and aroma, enhance flavor, and extend shelf life, high-barrier packaging materials are commonly employed. To measure WVTR makes it possible to determine the best packaging materials for food products[11].

The relationship of the WVTR and RH to the structure of the test samples. The chemical makeup of a polymeric material, specifically whether it is hydrophobic or hydrophilic, has an impact on the water vapor transmission rate (WVTR). Water vapor transmission rate depends on the different factors, such as the material thickness, chemical structure, chemical affinity for water. Material that has a high affinity for water is called as a hydrophilic material, the ones have a low affinity for water is known as hydrophobic material. Hydrophilic materials have polar or strongly interacting functional groups, such as -OH, -COOH and they swell or form hydrogen bonds with water molecules. On the other hand, hydrophobic materials repel water because of non-polar surface groups, such as hydrocarbons.

In this study, LDPE films were tested. LDPE is hydrophobic as it is composed of long hydrocarbon chains. LDPE films do not have chemical interaction with water molecules. Water vapor pass through the free-volume gaps or amorphous regions of LDPE. Additionally, it is worthwhile to mention that the water vapor concentration increases with the increase in the relative humidity. The water sorption for non-polar polymers is in minimum level, because water molecules do not dissolve strongly in polymer matrix. However, despite the low level of sorption, increase in water vapor concentration at the surface moderately increases the chance of water to pass through[12].

The effects of temperature and RH on the WVTR of the test samples. One of the factors that influence the WVTR is the environment temperature. Higher environment temperature, higher WVTR values and lower temperature, lower WVTR values. This phenomenon can also be easily observed from the WVTR table provided for this study. When it comes to how the temperature influences WVTR, there are several reasons. Water molecules have more kinetic energy in higher temperatures. This means the speed of molecules increase and they want to go to the lower humidity side by passing through the material used for food packaging[13]. Another reason is the polymer swelling. Increasing the environment temperature can make the polymer used for packaging more flexible, meaning that polymer chains loosen and open more space for water molecules pass through. In the study, LDPE films are were used, and it is semi-crystalline. Temperature affects the amorphous region of it[14].

When it comes to the effect of relative humidity, it creates the concentration gradient. The driving force for water molecules to pass through the packaging material increases with increase in the relative humidity. Water vapor move from high concentrated areas to low concentrates areas. The difference between relative humidity of the sides of packaging material is important. When this difference gets bigger, WVTR increases. Additionally,

there are several polymers, especially hydrophilic ones, absorb moisture from the environment when relative humidity is high, which leads to high WVTR values. In general, high relative humidity translates to high WVTR values. This phenomenon can be easily observed in our study with LDPE films It is also important to mention the combined effects of temperature and relative humidity. Looking at the data provided for LDPE films can help to investigate. High temperature and high relative humidity cause to the highest WVTR due to accelerated movement of the water molecules through material. Low temperature and low relative humidity lead to the lowest WVTR values. High temperature and low relative humidity result in lower WVTR values, while low temperature and high relative humidity have lower WVTR values than high temperature and high relative humidity, but still higher than low temperature and low relative humidity[14].

Comparison between experimental P and predicted P and reasoning. Predicted permeability values were calculated by using Van't Hoff-Arrhenius relationship and experimental permeability values were obtained from A part of the study. There are differences between these values and they can be explained by several reasons. Generally, predictions assume the ideal conditions, but real experiments are mainly performed under conditions that deviate from the assumptions. Moreover, the material permeability very sensitive to temperature and relative humidity. Small differences in temperature and relative humidity between experiment and assumed conditions can create discrepancies in the final result.

Conclusion

The water vapor transmission rate (WVTR), permeance, permeability are important quantities to measure for packaging materials. In the given study, activation energy, predicted permeability values of LDPE films and pouches were calculated and compared. In the first part, the water vapor permeability studies were carried out at three different temperatures with each temperature subjected to 50% and 100% relative humidity values. Van’t Hoff-Arrhenius relationship is used to find the activation energies for each replicate. The effects of temperature and relative humidity were discussed. In the second part, four poches were made and placed in a chamber where temperature is 37.8^{o}C and relative humidity is 85%. The weight gain was determined and plotted as a function of time. The reasons for the difference between predicted and experimental permeability values were investigated.

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